National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

A Natural Resource Condition Assessment for Sequoia and Kings Canyon National Parks

Appendix 22 – Climatic Change

Natural Resource Report NPS/SEKI/ NRR—2013/665.22

ON THE COVER
Giant Forest, Sequoia National Park
Photography by: Brent Paull

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Contents

Figures

Tables

Scope of Analysis

Climate is a master controller of the structure, composition, and function of biotic communities, affecting them both directly, through physiological effects, and indirectly, by mediating biotic interactions and by influencing disturbance regimes. Sequoia and Kings Canyon National Park's (SEKI's) dramatic elevational changes in biotic communities -- from warm mediterranean to cold alpine -- are but one manifestation of climate's overarching importance in shaping SEKI's landscape.

Yet humans are now altering the global climate, with measurable effects on ecosystems (IPCC 2007). Over the last few decades across the western United States, human-induced climatic changes have likely contributed to observed declines in fraction of precipitation falling as snow and snowpack water content (Mote *et al.* 2005, Knowles *et al.* 2006), advance in spring snowmelt (Stewart *et al.* 2005, Barnett *et al.* 2008), and consequent increase in area burned in wildfires (Westerling *et al.* 2006). In the Sierra Nevada, warming temperatures have likely contributed to observed glacial recession (Basagic 2008), uphill migration of small mammals (Moritz *et al.* 2008), and increasing tree mortality rates (van Mantgem and Stephenson 2007, van Mantgem *et al.* 2009). More substantial changes can be expected for the future (e.g., IPCC 2007).

Given the central importance of climate and climatic changes, we sought to describe long-term trends in temperature and precipitation at SEKI. Time and budget constraints limited us to analyses of mean annual temperature and mean annual precipitation, using readily-available data. If funds become available in the future, further analyses will be needed to analyze trends by season, trends in daily minimum and maximum temperatures, and so on.

We chose to analyze data from individual weather stations rather than use interpolated climatic data from sources such as PRISM (http://www.prism.oregonstate.edu/). In topographically complex mountainous regions with few weather stations, like SEKI, the addition or subtraction of even a single weather station through time has the potential to significantly bias trends in interpolated data. In particular, this analysis was motivated by our questioning of some PRISM results presented in Appendix 1 (Landscape Context) that compared temperature averages between two 30-year periods of the 20th Century. Figures 6 and 11 of Appendix 1 indicate that recent (1971-2000) temperatures in northern Kings Canyon National Park averaged some 2° C cooler than those of 1911-1940. This would represent a truly profound and persistent cooling, and seems to be at odds both with the glacial retreats observed in the area over the century (Basagic 2008), and with the reported PRISM warming of nearly 2° C just to the west of the cooling (see Figs. 6 and 11 in Appendix 1). We suspect that the extreme localized Kings Canyon cooling reported by PRISM is an artifact of sparsely-distributed weather stations in the region being added and discontinued over the span of the 20th Century. For example, data from the Western Regional Climate Center (http://www.wrcc.dri.edu/coopmap/) suggest that for the period 1911 through 1924 PRISM must interpolate northern Kings Canyon temperatures based on a few low-elevation stations -- separated by hundreds of kilometers -- in Nevada and California's San Joaquin Valley. In contrast, by 1970 PRISM interpolations will be dominated by closer, higher-elevation stations (see this report). The single weather station closest to northern Kings Canyon that has a temperature record at least partly spanning Appendix 1's two

30-year time periods -- the Independence station, with a relatively continuous temperature record starting in 1925 -- shows a modest warming, not a cooling, between 1925-1940 and 1971-2000, further casting doubt on the Kings Canyon cooling shown in Figs. 6 and 11 of Appendix 1. If funds become available, it will be useful to more formally analyze potential PRISM biases in long-term SEKI climatic trends. Until then, the analyses of individual weather station records presented here (effectively an analysis of source data that PRISM uses) are meant to provide a robust summary of climatic changes in SEKI.

Critical Questions

This chapter addresses three questions:

(1) Over the last several decades in SEKI, has mean annual temperature changed?

(2) Over the last several decades in SEKI, has mean annual precipitation changed?

(3) Can we generalize the preceding results -- which are based on data from individual weather stations -- to the whole park landscape?

Data Sources and Types Used in Analysis

Station Selection

After a multi-decadal hiatus, starting in about 1975 global temperatures resumed their climb to present levels (http://data.giss.nasa.gov/gistemp/graphs_v3/). For our SEKI analyses we therefore chose to compare 1975-2011 temperatures with those from at least a 20-year reference period preceding 1975; that is, we sought weather stations with continuous temperature records spanning at least 1955-2011. (See **Processing Temperature and Precipitation Records**, below, for a description of what constituted "continuous" records for our purposes.) We further desired that (1) all weather stations occurred within SEKI boundaries, (2) at least two stations each were found at low, middle, and high elevations (<1500 m, 1500-3000 m, and >3000 m, respectively), and (3) at least one station each was found in the Kaweah, Kern, and Kings watersheds.

However, even though Davey *et al.* (2007) identified 55 weather and climate stations within SEKI boundaries, most records are short or fragmentary and only two stations met all of our desired criteria: Ash Mountain (low elevation) and Grant Grove (middle elevation). We therefore relaxed our criteria to allow us to include either (1) the closest weather station within the Kaweah, Kern, or Kings watersheds but outside of SEKI boundaries, or (2) stations within SEKI boundaries that had continuous temperature records starting between 1955 and 1975 (i.e., with any data beginning within our desired ≥20 year reference period). The first relaxed criterion allowed us to capture a second low-elevation station -- Lemon Cove -- and the second relaxed criterion allowed us to capture a second middle elevation station -- Lodgepole.

Even with our relaxed criteria, we were left with stations concentrated only in the southwestern part of our study area, and none at high elevations. To expand our geographic coverage to the east and the north, we therefore included the closest two stations with continuous temperature records spanning at least 1955-2011 to the east of the Sierran crest: Independence and Bishop Airport. We also included high-elevation stations within SEKI boundaries that had continuous temperature records spanning at least the last 20 years (i.e. at least 1992-2011): Bishop Pass, Charlotte Lake, and Chagoopa Plateau. Thus, while we could not analyze recent high-elevation temperatures relative to a pre-1975 reference period, we could still determine whether high-elevation temperatures had been changing over the last 20 or more years.

We obtained data for the three high-elevation stations from the Department of Water Resources California Data Exchange Center website (http://cdec.water.ca.gov/staMeta.html). These three high-elevation stations also record snowpack water content but not total precipitation, and so were not used in our analyses of precipitation trends. The six remaining stations are NOAA COOP stations, and we obtained their data from the Western Regional Climate Center website (http://www.wrcc.dri.edu/coopmap/). All six COOP stations had precipitation data adequate for our analyses.

Processing Temperature and Precipitation Records

For the six NOAA COOP stations (Lemon Cove, Ash Mountain, Independence, Bishop Airport, Grant Grove, and Lodgepole), the Western Regional Climate Center website (http://www.wrcc.dri.edu/coopmap/) provides summary data in a monthly time step. Monthly averages of temperature are not provided for months in which data were missing for 26 or more days. We calculated the average temperature of missing months as the average of the surrounding months (e.g., if July was excluded, the average July temperature was calculated as the average of the June and August average temperatures). If more than two consecutive months were missing, then that entire year for that station was excluded from our temperature analyses. We then calculated average annual temperature for a station as the average of the calendar year's average monthly temperatures. Annual precipitation was calculated as the sum of monthly precipitation for the calendar year (not the water year). For precipitation, we excluded any year in which data were missing for 26 or more days in more than two months.

Temperature data for high elevations (>3000 m), from the Department of Water Resources California Data Exchange Center website (http://cdec.water.ca.gov/staMeta.html), are provided in an hourly time step. To calculate average annual temperature, we first calculated average monthly temperature using all available hourly measurements for a given month, then calculated average annual temperature as the average of the monthly values. (This approach was meant to emulate our analysis of the NOAA COOP stations, in which each month is given equal weight regardless of the number of valid temperature observations in the month.) We excluded as errors any hourly temperature values of greater than 120°F or less than -50°F. If a given month did not have at least one valid temperature measurement representing each hour (midnight through 11 p.m., whether or not those measurements occurred on the same day), then data from that month were excluded from the analysis. This procedure excluded months with excessive missing data and months for which data collection may have been biased (e.g., if only daylight temperatures were recorded). For excluded months, average temperature was estimated as the average of the surrounding months (e.g., if July was excluded, the average July temperature was calculated as the average of the June and August average temperatures). If more than two consecutive months were missing, then that entire year for that station was excluded from our temperature analyses. Coupled with our requirement that high elevation stations have ≥20 years of continuous annual temperature records (see the preceding subsection), our requirements resulted in us dropping from consideration the high-elevation Crabtree, Upper Tyndall, and State Lakes stations within SEKI's boundaries, leaving us with the high elevation records from Bishop Pass, Charlotte Lake, and Chagoopa Plateau. Precipitation records were not available for these high elevation stations.

Note that for all nine stations in our temperature analyses, temperatures were interpolated for relatively few months at each station (Table 1).

Table 1. Number of months for which temperature was interpolated for each station.

Station	# of months interpolated	Total # of months
Lemon Cove	0	744
Ash Mountain	3	744
Independence	13	744
Bishop Airport	0	744
Grant Grove	5	744
Lodgepole	5	504
Chagoopa Plateau	0	240
Charlotte Lake	1	240
Bishop Pass	4	240

Note: This includes only the periods used in our analyses.

Table 2. Station Information

Station	Elevation (m)	Year of Establishment	Start of Unbroken Record
Lemon Cove	156	1899	1909
Ash Mountain	521	1927	1949
Independence	1204	1893	1949*
Bishop Airport	1250	1948	1949
Grant Grove	2012	1940	1949
Lodgepole	2053	1968	1969
Chagoopa Plateau	3139	1986	1991
Charlotte Lake	3170	1985	1991
Bishop Pass	3414	1988	1989

* Independence has an unbroken record of temperature starting in 1949, but 1997 precipitation data were excluded due to missing data.

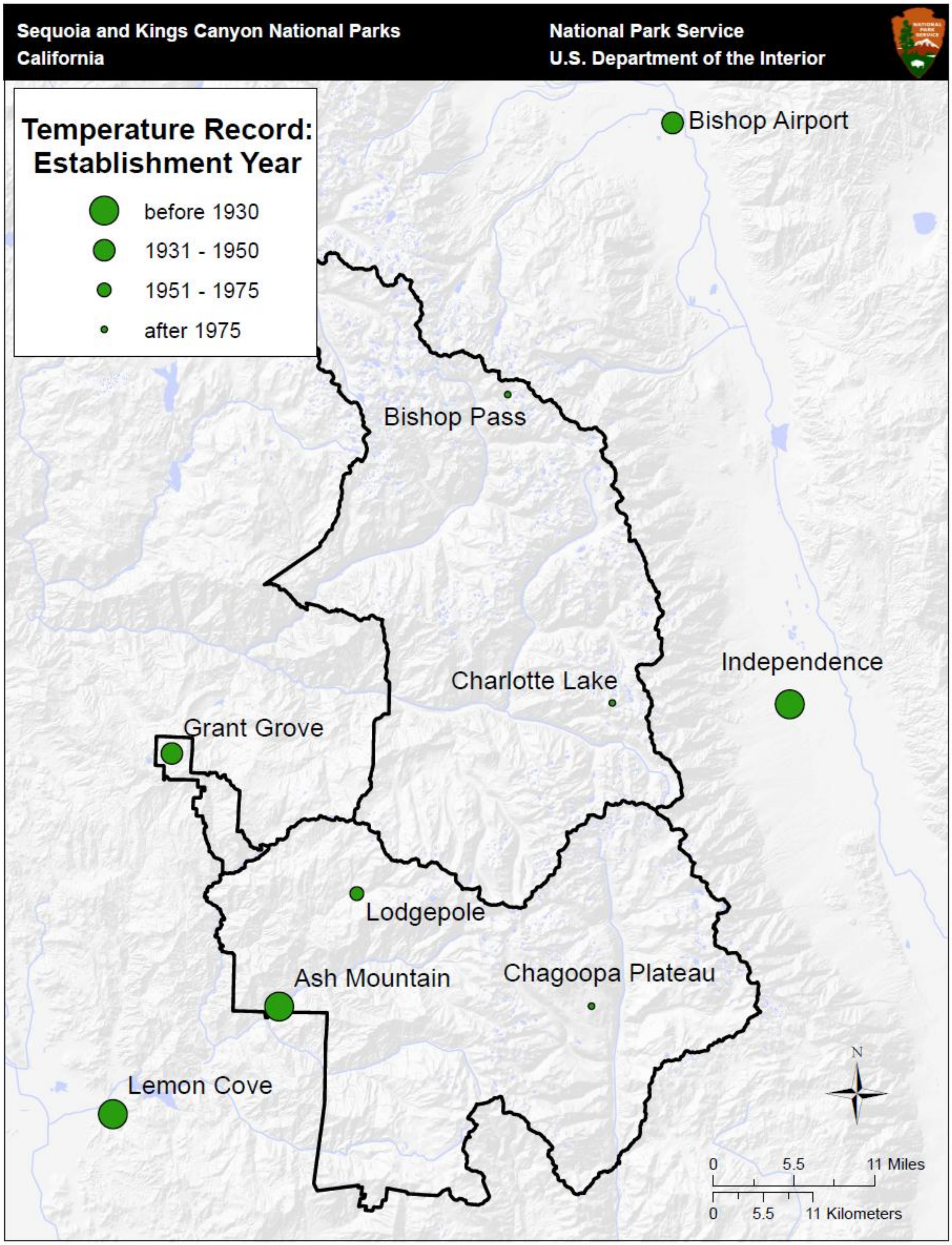

Figure 1. Station locations and years of establishment.

Reference Conditions

After a multi-decadal hiatus, starting in about 1975 global temperatures resumed their climb to present levels (http://data.giss.nasa.gov/gistemp/graphs_v3/). For our SEKI analyses we therefore chose to compare 1975-2011 temperatures with those from at least a 20-year reference period preceding 1975; that is, we sought weather stations with continuous temperature records spanning at least 1955-2011. (See **Processing Temperature and Precipitation Records**, above, for a description of what constituted "continuous" records for our purposes.) Five stations met this criterion, one with continuous temperature records starting in 1909, and the other four with continuous records starting in 1949 (Table 2). We therefore chose 1949-1974 as our reference period for both temperature and precipitation (Table 3).

Table 3. Reference period temperature and precipitation for the five stations with records spanning the reference period.

Station	Mean Temperature 1949 to 1974 (°C)	Mean Preciptiation 1949 to 1974 (cm)
Lemon Cove	17.26 (0.13)	33.9 (2.3)
Ash Mountain	17.22 (0.12)	63.9 (4.2)
Independence	15.09 (0.13)	13.0 (1.6)
Bishop Airport	13.37 (0.10)	14.3 (1.6)
Grant Grove	7.65 (0.11)	108.0 (6.6)

Note: Number in parentheses is the standard error.

The mean reference period temperature for these five stations was 14.12 °C (s.e. 0.32); mean precipitation was 46.6 cm (s.e. 3.6).

Temporal Analyses

Figures 2 and 3 summarize the full temperature and precipitation records for all nine weather stations used in our analyses, with separate graphs for stations at low, middle, and high elevations (<1500 m, 1500-3000 m, and >3000 m, respectively).

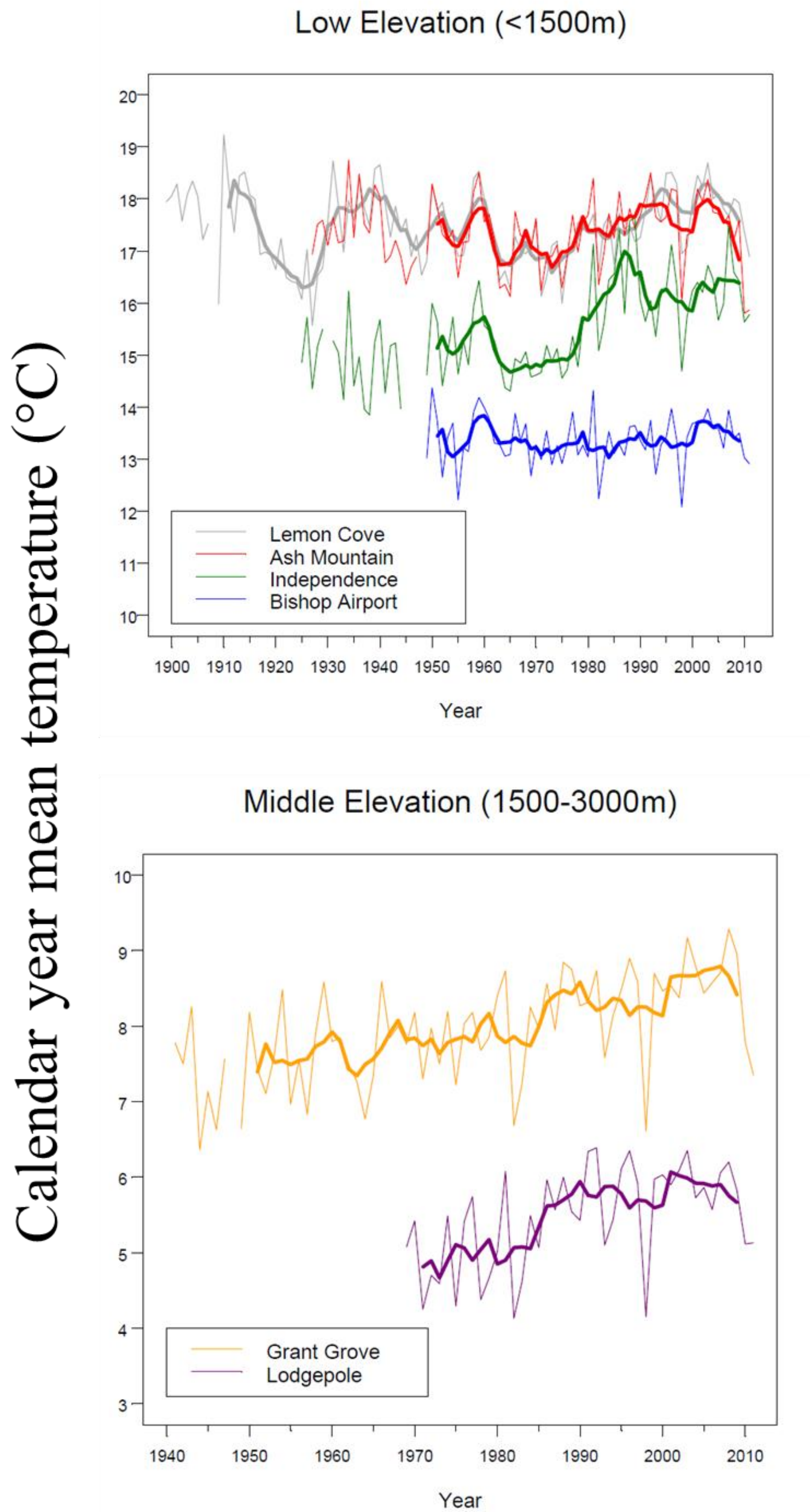

Figure 2. Temperature records for stations examined in the analysis. Thick lines are five-year running averages, spanning the period of continuous record for each station. Gaps are years that were excluded due to missing data. (The figure is continued on next page.)

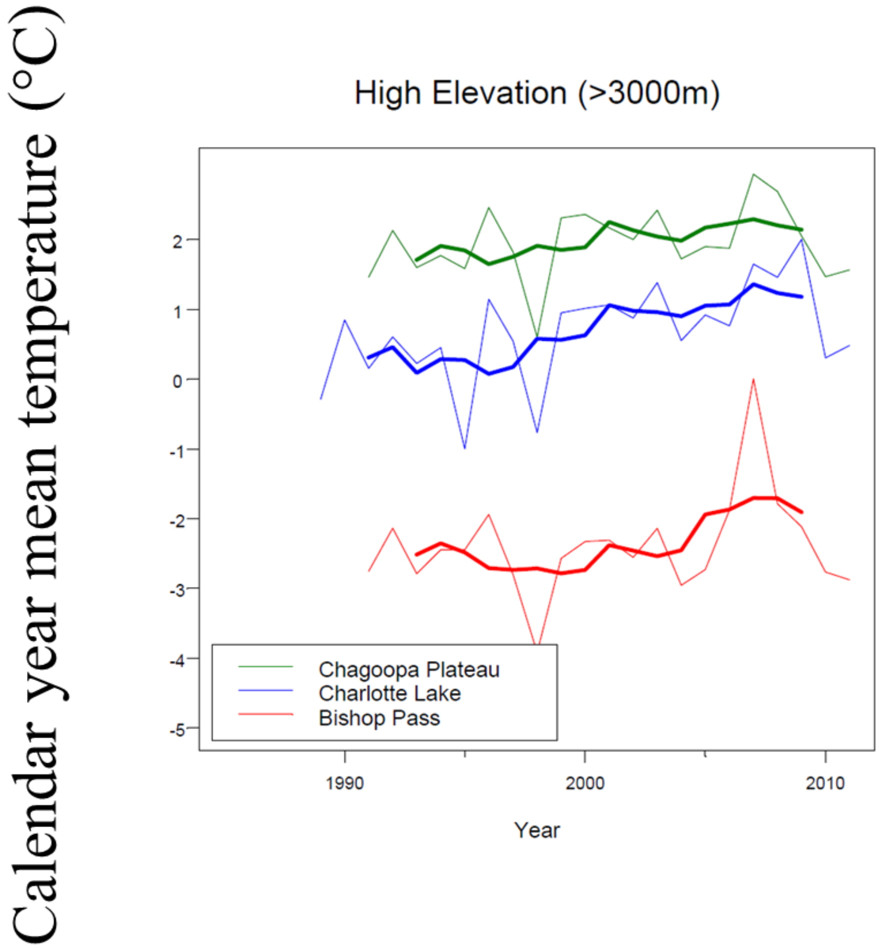

Figure 2. (Continued from previous page.) Temperature records for stations examined in the analysis. Thick lines are five-year running averages, spanning the period of continuous record for each station. Gaps are years that were excluded due to missing data.

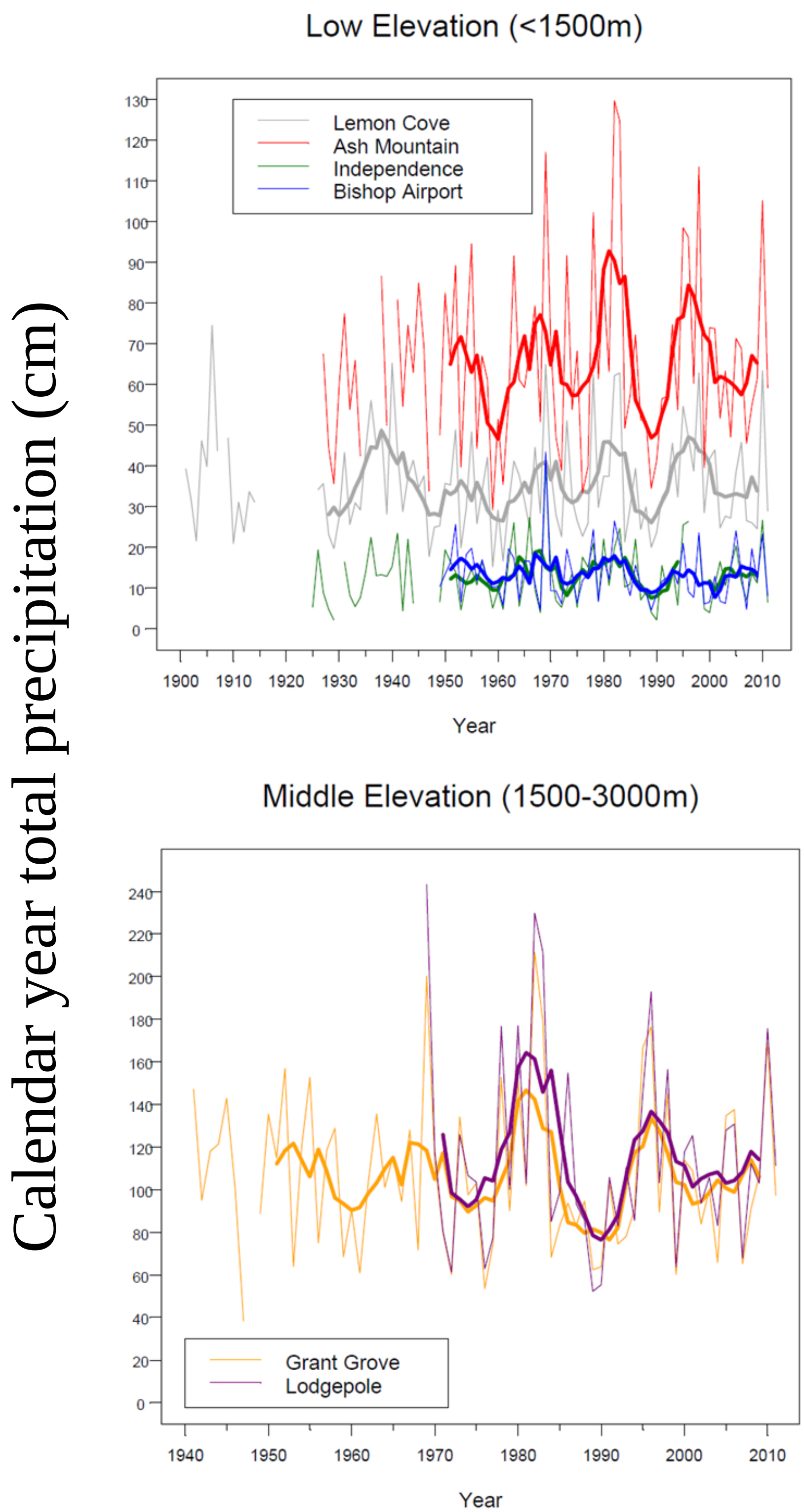

Figure 3. Precipitation records for stations examined in the analysis. Thick lines are five-year running averages, spanning the period of continuous record for each station. Gaps are years that were excluded due to missing data. No precipitation data were available for high elevation stations.

For our temporal analyses, we compared mean temperature and precipitation of the reference period (1949 to 1974) with mean temperature and precipitation of the recent period (1975 to 2011), as well calculating linear temperature and precipitation trends across the full (1949 to 2011) and recent (1975 to 2011) periods. For both sets of analyses, we used linear mixed effect models with station identity as a random variable and time period (reference or recent) or year as a fixed effect. We found evidence at some stations of temporal autocorrelation in temperatures at a lag of one year (i.e., current year temperature is in part related to the prior year temperature), so we also used a one year autoregressive model in our temperature analyses. We found little evidence of autocorrelation in the precipitation data, so we did not also use an autoregressive model in our precipitation analyses.

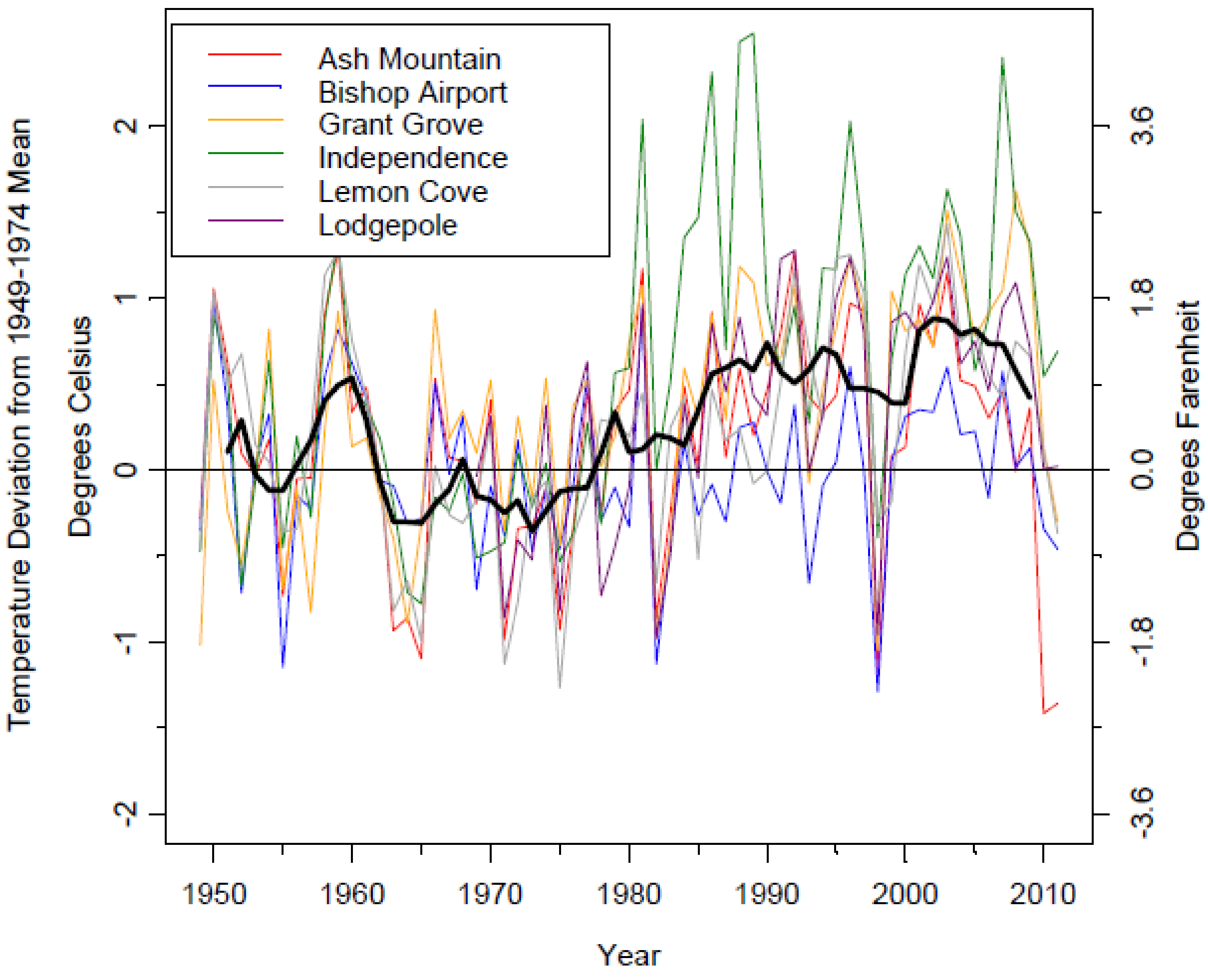

Figure 4. Deviations in temperature from the reference period (1949-1974) means. The thick black line is the five year running mean of the average of all six stations. The reference period mean for the Lodgepole station (which started in 1969) was adjusted to account for potential bias in its shorter reference period by calculating the average difference between the 1949-1974 mean and the 1969-1974 mean for all of the other stations and then adjusting the Lodgepole mean by this amount.

For the comparison of means between time periods, we used the five stations with unbroken records since 1949 (Table 2). The mixed models indicated a significant difference in temperature between the reference and recent periods, with a mean increase of 0.37°C (0.10 s.e., $p<0.01$) in the recent period. Fitting a linear trend also demonstrated a significant positive slope with year for both the full 1949 to 2011 period (0.011°C/year, s.e. 0.003, $p<0.01$) and for the 1975 to 2011 period alone (0.016°C/year, s.e. 0.005, $p<0.01$). For the latter fit, we included all six stations with complete records since 1975 (i.e., we also included Lodgepole). Using the slope from the latter model, we can estimate that the mean increase in temperature from 1975 to 2011 across the six stations has been about 0.58 °C. This increase is especially evident once the station records are normalized to temperature deviations from the reference period (temperature of a given year minus the mean for the reference period) and then plotted as a moving average (Fig. 4).

Although reference period temperature data were not available for our three high elevation stations (Chagoopa Plateau, Charlotte Lake, and Bishop Pass), we analyzed the 1991 to 2011 linear temperature trend of these stations taken as a group (using a mixed model and corrected for temporal autocorrelation). The high elevation stations showed an increasing trend in temperature for the last two decades (0.032°C/year, s.e. 0.015, $p=0.04$).

Similar to the findings of Diaz and Eischeid (2007) for the Sierra Nevada as a whole, preliminary analyses (not shown) suggested that the rate of warming at SEKI might increase with elevation. However, a more thorough analysis using an expanded dataset will be required to adequately test this possibility.

Our analyses for precipitation showed no significant differences in mean precipitation between the reference and recent periods and no significant linear trends through time. The lack of a systematic change in precipitation is evident when precipitation is normalized for each station (in this case as the percent deviation from the reference period mean) and plotted as a moving average (Fig. 5).

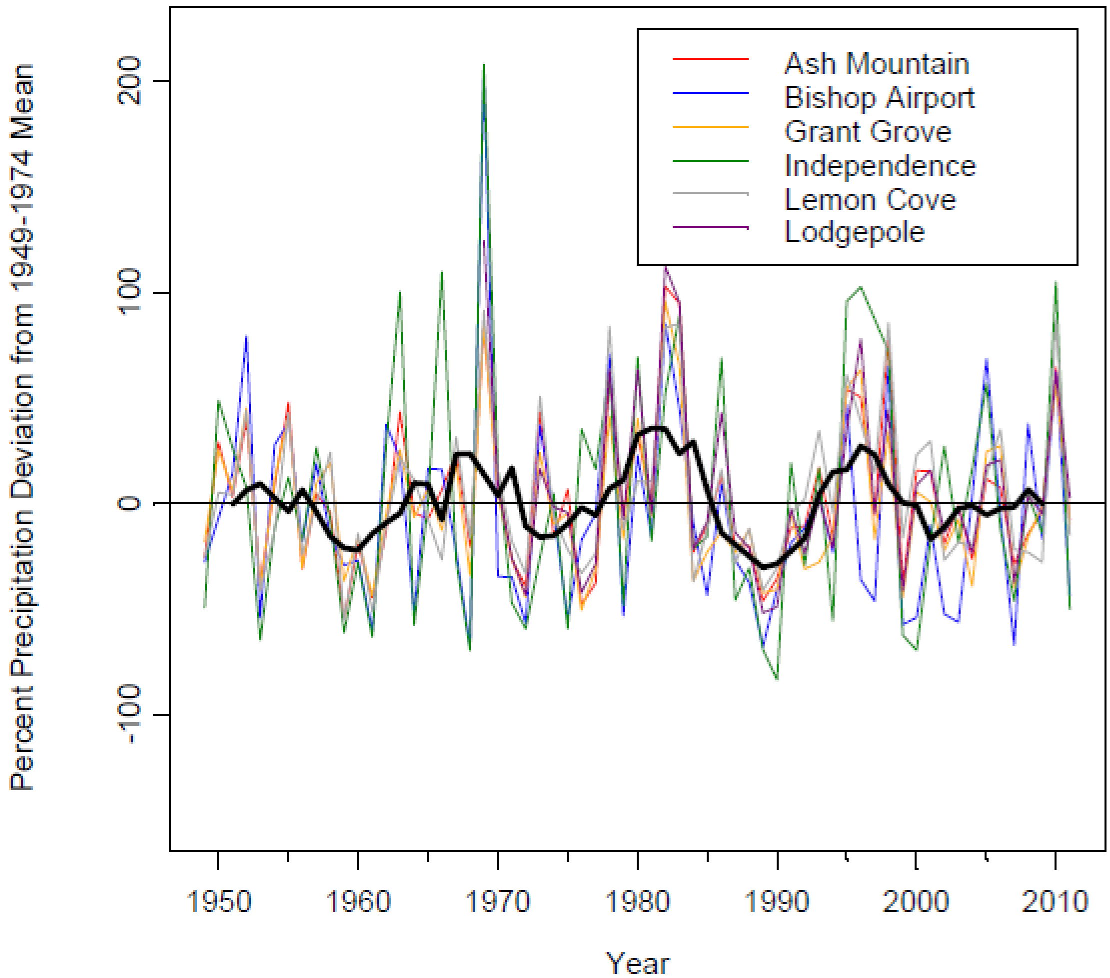

Figure 5. Percent deviations in precipitation from the reference period (1949-1974) means. Thick black line is the five year running mean of the average of all six stations. The reference period mean for the Lodgepole station (which started in 1969) was adjusted to account for potential bias in its shorter reference period by calculating the average ratio between the 1969-1974 mean and the 1949-1974 mean for all of the other stations and then adjusting the Lodgepole mean by dividing by this correction factor.

For both temperature and precipitation, temporal changes recorded by the SEKI weather stations largely paralleled those of California as a whole (Fig. 6), consistent with our expectation that SEKI's climate is a consequence of larger regional climatic phenomena.

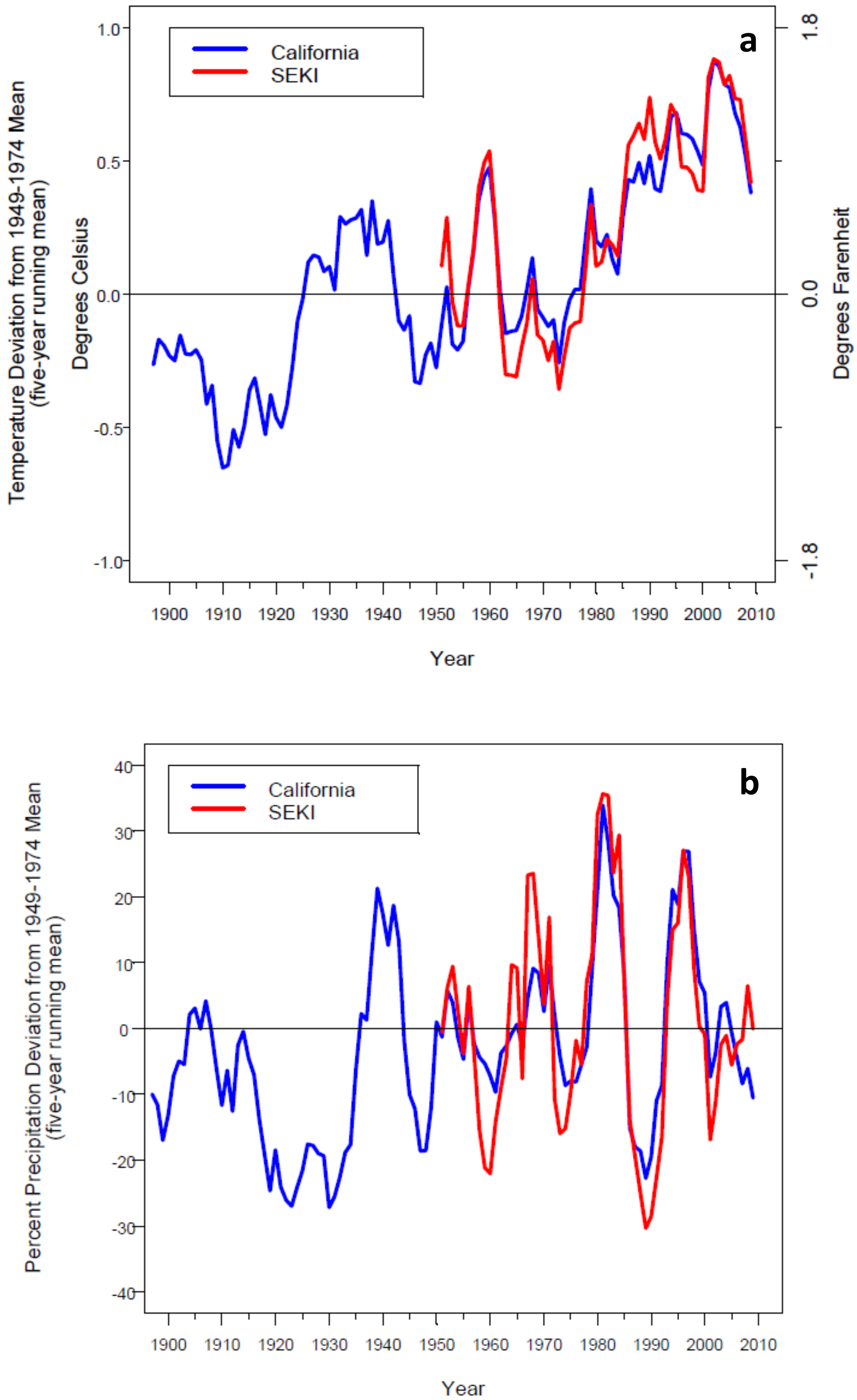

Figure 6. (a) Temperature deviations from the reference period (1949-1974) means for SEKI and vicinity weather stations (red) and for California as a whole (blue). (b) Precipitation deviations (normalized as percentage deviations) from the reference period (1949-1974) means for SEKI and vicinity weather stations (red) and California as a whole (blue). Temperature and precipitation data for California as a whole were obtained from the Western Regional Climate Center's California Climate Tracker (http://www.wrcc.dri.edu/monitor/cal-mon/index.html).

Analysis Uncertainty

Due to time and funding constraints, our analysis was limited in both breadth and depth, only including weather stations within or in the immediate vicinity of the parks and, of those, only stations meeting our data criteria. This resulted in only a few weather stations being available for our analysis, and these stations were not distributed throughout all the HUC 10 watersheds in SEKI (although the larger Kings, Kern, and Kaweah watersheds each contained at least one temperature station). Furthermore, although we corrected for any gross errors or biases in the station data, we did not conduct a thorough error assessment and correction for each station. Such an analysis would include accounting for any weather station moves, accounting for potential changes in the environment in the immediate vicinity of the station (e.g., construction of a parking lot), a more in-depth analysis of missing data and possible data in-filling, and the development of algorithms to test for human and instrumental error in the data (beyond the simple check for gross errors used in our analysis).

For these reasons, we focused on analyses of several stations together rather than single stations (which individually may have biases in their records). The good match between our calculated temperature and precipitation trends in SEKI and vicinity and those for California as a whole gives us some added confidence in our results.

Nonetheless, results should be interpreted with caution. For example, while we are confident in our assessment that temperatures have been increasing throughout SEKI, the magnitude of the increase could vary by location. For example, the magnitude of temperature increase might increase with elevation (Diaz and Eischeid 2007), and conceivably could vary among SEKI's watersheds.

Interactions with Other Focal Resources

As noted earlier, climate is a master controller of the structure, composition, and function of biotic communities, affecting them both directly, through physiological effects, and indirectly, by mediating biotic interactions and by influencing disturbance regimes. Changes in climate are therefore likely to interact with virtually every other focal resource in the parks. Please refer to individual NRCA focal resource chapters for discussions of how each resource might interact with climate (found generally in the "Stressors" sections, though it is important to note that not all chapters contain discussions of climate change interactions).

Stressors

Unlike many other focal resources in the NRCA report, climatic change is itself a stressor rather than being subject to them. Please refer to individual NRCA chapters for discussions of how climate change might affect given focal resources.

Assessment

In response to our original three "Critical questions," our analysis of individual weather station data indicated that (1) SEKI temperatures have increased over the last few decades, (2) precipitation has not detectably changed, and (3) with a reasonable degree of confidence we can generalize these results to the whole SEKI landscape. We detail these assessments below.

Recent temperatures at the weather stations we analyzed have increased relative to the 1949-1974 reference period, increasing at a rate of about 0.16 °C decade^{-1} (0.29 °F decade^{-1}) since 1975. Total warming from 1975 through 2011 has been about 0.58 °C (1.0 °F), somewhat less than the warming reported by Diaz and Eischeid (2007) for the Sierra Nevada as a whole for the period 1979-2006. Temperature appears to have increased at all elevations, with some hint that the rate of temperature increase might increase with elevation (Diaz and Eischeid 2007 reached a similar conclusion for the entire Sierra Nevada) -- a possibility that could be tested using a larger sample of stations from the southern Sierra Nevada.

Although our weather stations sampled only a few locations within SEKI's boundaries (Fig. 1), we have reason to believe our qualitative observation of increasing temperature is representative of the SEKI landscape as a whole. Climate, by nature, is a regional phenomenon, and our stations were fairly well distributed geographically (Fig. 1). With the exception of the weather station most distant from SEKI (Bishop Airport in the Owens Valley, which showed a miniscule temperature decline that was statistically indistinguishable from no change; see Fig. 2), individual weather stations with continuous records since 1949 showed warmer mean temperatures for 1975-2011 than for the reference period 1949-1974. All of the remaining stations (those with shorter records: Lodgepole and the three high elevation sites) showed warming trends over the lengths of their records. Finally, our temperature data closely tracked those for California as a whole (Fig. 6a), adding to our confidence that temperature as recorded by our stations reflects climate as a larger regional phenomenon.

Turning to precipitation, we found that SEKI precipitation has been highly variable through time (Figs. 3, 5, and 6b), but we could detect neither differences in mean precipitation between 1949-1974 and 1975-2011, nor linear trends in precipitation. As with temperature, we expect mean annual precipitation to behave as a regional phenomenon. Indeed, periods of high and low precipitation in SEKI correspond to similar periods in California as a whole (Fig. 6b). The data for California as a whole suggest that California was drier from 1900 to the late 1930s than from the late 1930s to the present (Fig. 6b); however, more work is needed to determine with confidence whether this is also true for the southern Sierra Nevada.

Although temperature increased relative to the reference period, we did not assign condition classes based on the magnitude of temperature increase, as we know of no Sierra-specific literature reviews of empirical studies tying given magnitudes of temperature change to given magnitudes of ecosystem impact. Instead we chose condition classes based on the observed effects of increasing temperature on ecosystems. In the absence of a rigorous quantitative way to accomplish this, we chose qualitative categories for our condition classes: "good" condition indicates that increasing temperature has had no measurable effect on ecosystems, "moderate" condition indicates that some modest temperature effects have been detected (see the next paragraph), and “poor” condition means some relatively severe temperature effects have been detected (such as large areas of climate-driven forest die-back, unusually severe wildfires, or substantial hydrologic changes).

Within SEKI’s boundaries, warming temperatures have been implicated both in glacial recession (Basagic 2008) and in increasing background tree mortality rates (van Mantgem and Stephenson 2007, van Mantgem *et al.* 2009). In Yosemite to the north, increasing temperatures have also been implicated in an observed upward migration of small mammals (Moritz *et al.* 2008); similar upward migrations may have occurred in SEKI, but data are currently inadequate to judge. We therefore judge the condition class for temperature to be “moderate” (Fig. 7); that is, relatively modest effects on ecosystems have been detected.

Since we detected no directional change in precipitation relative to our reference period, we judged our condition class for precipitation to be “good” (Fig. 8).

We also wished to assign a condition class to climate as a whole. However, we deemed it inappropriate to simply average the conditions classes for temperature and precipitation. First, the effects of temperature and precipitation changes on vegetation are not additive; rather, they are nearly orthogonal (Stephenson and Das 2011). Second, our definition of condition classes for climate as a whole logically should be the same as that for temperature or precipitation separately: “good” condition indicates that climatic changes as a whole have had no measurable effect on ecosystems, “moderate” condition indicates that some modest effects have been detected, and “poor” condition means some relatively severe effects have been detected. As described earlier, moderate effects of climatic changes have been detected -- they just happen to be the consequence of temperature changes alone. We therefore judge the condition class for climate as a whole to be “moderate” (Fig. 9).

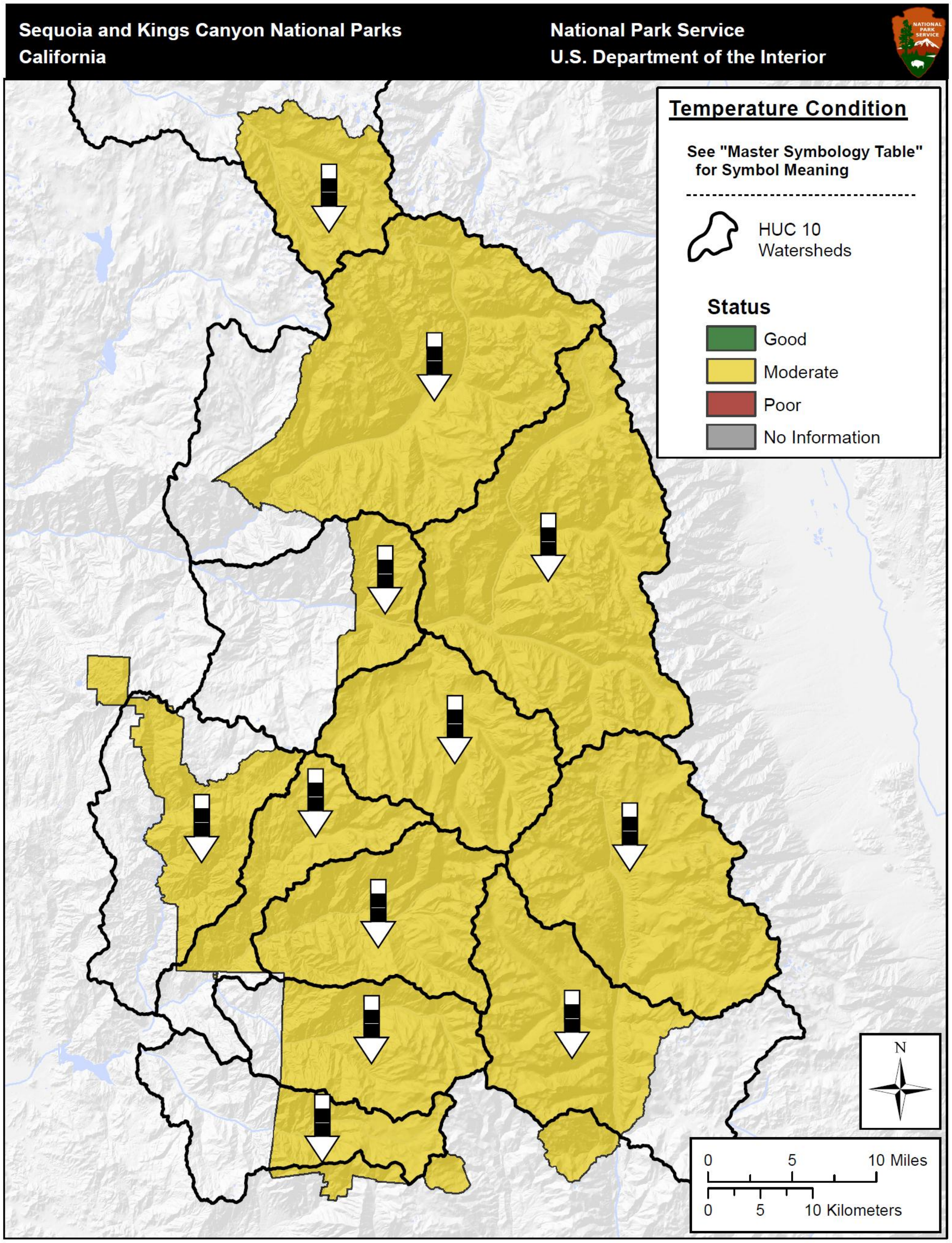

Figure 7. Weather station data indicated that warming has almost certainly been a regional phenomenon, so that our “moderate” condition assessment (based on the observed effects of warming on SEKI and related Sierra Nevada ecosystems) was applied throughout the park.

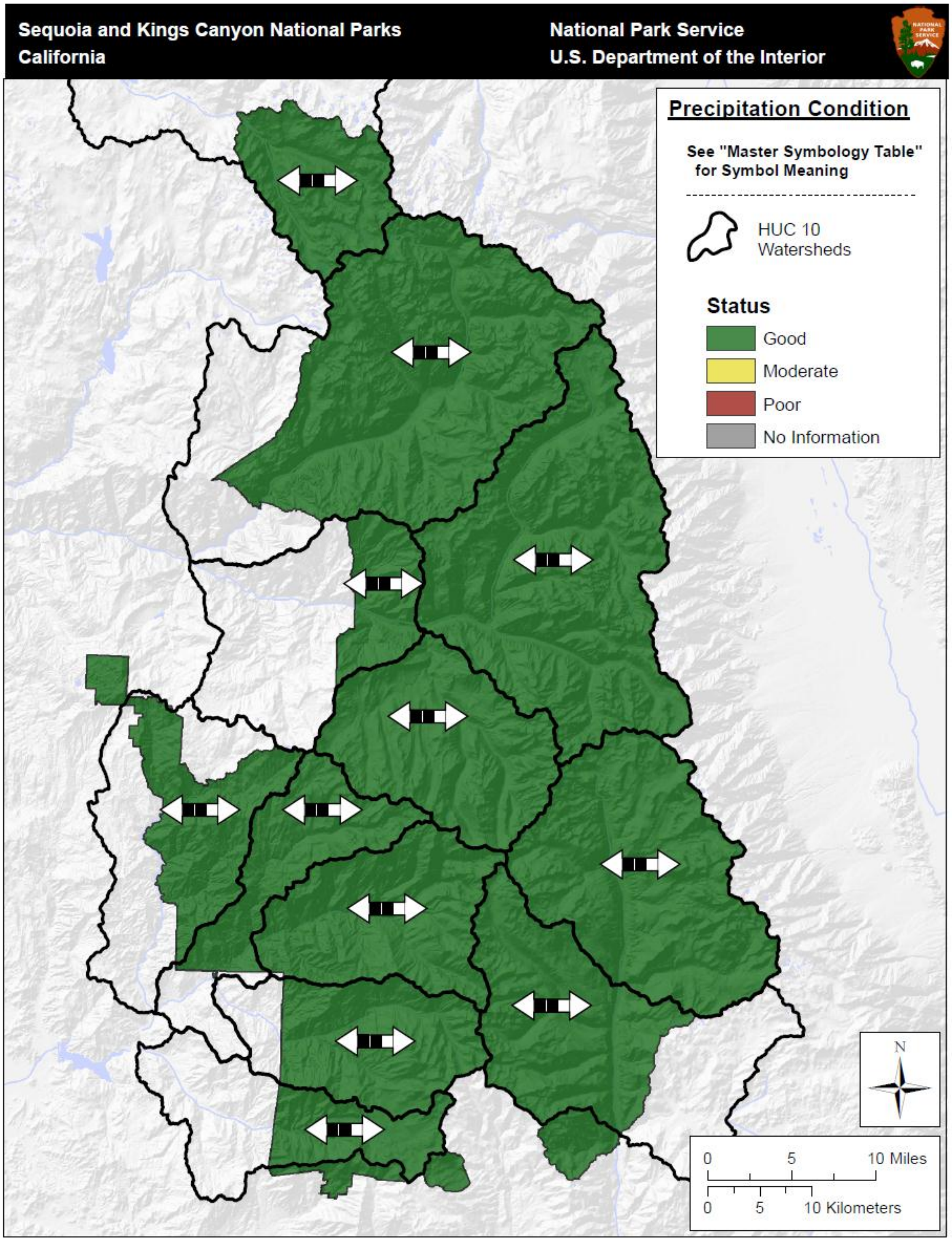

Figure 8. In agreement with regional patterns, weather station data showed no directional trend in precipitation over time. The condition was therefore assessed as “good” throughout the park.

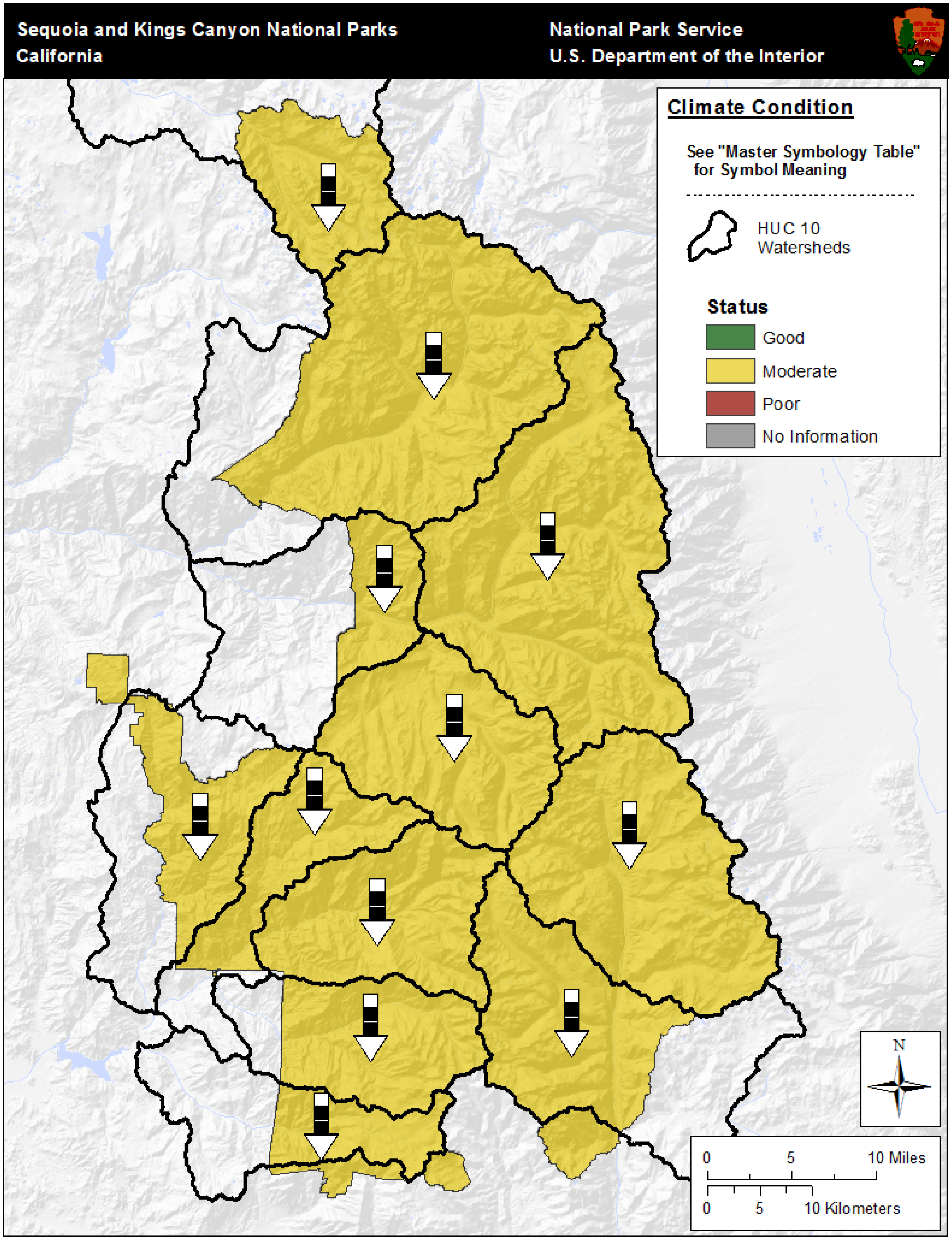

Figure 9. Moderate changes due to climatic effects have been detected in the parks, apparently as a consequence of temperature changes. We therefore judge the condition class for climate as a whole to be “moderate”

Level of Confidence in Assessment

As noted in the **Analysis Uncertainty** section, we are confident of our assessment that temperatures have been increasing throughout the parks and that there has not been a marked directional change in precipitation. This confidence is bolstered by the general agreement between the patterns seen in SEKI weather stations and those for California as a whole. Our confidence is lower in the precise magnitudes of temperature changes at different locations across the SEKI landscape.

Gaps in Understanding

The main causes of the uncertainties we discussed earlier are deficiencies in both the spatial and temporal coverage of weather station data in SEKI and vicinity. Thus our primary gaps in understanding are (1) the details of SEKI climatic trends before 1949, and (2) the nature of any systematic spatial variation in the magnitude of climatic changes across the SEKI landscape. In both cases, climate proxies from tree rings could help partially fill these gaps in understanding, as could the studies recommended below.

Recommendations for Future Study and Research

We make three primary recommendations for future research:

1) Analyses should be extended to the southern Sierra Nevada region as a whole, thus incorporating many more weather stations. Such an extended analysis might provide a longer regional record that spatially brackets SEKI, allowing us both to infer longer-term trends within SEKI and to increase our confidence in our conclusions specific to SEKI.

2) As a particularly important part of this extended analysis, emphasis should be given to determining whether temperatures have increased more rapidly at higher elevations.

3) Given the potentially great value of weather interpolation algorithms (such as PRISM) for informing our understanding of climatic changes in SEKI, potential biases in such algorithms should be identified and, if possible, corrected.

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